

Explicit Guidance Scheme for a three stage Solid propelled launch vehicle with a Velocity Correction Module

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Abstract

The design of an explicit guidance algorithm for a multi-stage solid motor propelled launch vehicle is challenging due to non-availability of thrust cut-off provision. As the thrust cannot be terminated upon reaching the designated target, energy management for a completely solid propelled launch vehicle is difficult. Precise orbit injection catering for a wide range of dispersions gets even more complicated. This paper discusses the Guidance algorithm design for a three-stage solid motor propelled launch vehicle together with a Velocity Correction Module as the terminal stage for fine velocity correction. The guidance strategy evolves by identifying the target parameters that can be met one after the other during each of the stages and thus achieving a close-to-perfect target orbit at the end of third stage and later enabling the Velocity Correction Module to correct for the dispersions in a single burn. The algorithm was validated for additive propulsion dispersion scenarios and the results discussed.

Keywords: •Explicit Launch Vehicle Guidance
• Solid Motor Guidance • Velocity Correction
Module

1. Introduction

History of Solid rockets started back in 11th Century AD with gun powder as propellant. The rocketry did not evolve much in the following centuries up till the 18th when Tipu Sultan identified the applications of solid rockets in the art of war. Solid rockets are used today worldwide, in defence and space exploration applications for their reliability and simplicity with almost zero moving parts. Solid rockets can

provide high thrust for relatively low cost. They are used as booster stages with which the launch vehicle can cross the atmospheric barrier within a short period of time thus reserving high specific impulse, less massive cryogenic engines for upper stages. When we list down the advantages of the solid rocket stages, it is equally important to mention that these advantages come at a cost. Solid motors pose difficulties in propulsion modelling and performance evaluation thereby challenging the guidance subsystem designers.

Solid rocket motors do not offer much flexibility with respect to energy management because there is no luxury of cutting off the engine thrust as soon as a predefined target has been achieved. Usually, a solid motor is followed by a liquid engine that can compensate for the propulsion deviations of the solid stage by consumption of additional fuel loading. When it comes to multiple solid stages stacked one over the other, dispersions in the lower stages gets carried over to the upper stage but the upper stage is unable to compensate for the deviations as there is neither additional fuel available nor a provision for early cut-off. Even though a few multi-stage solid propelled launch vehicles such as Pegasus, Minotaur and Epsilon exist around the world, the agencies who developed these launchers clearly understood the difficulties in achieving precise orbits with an all-solid launch vehicle and opted for simple on-board guidance strategies thus accepting the inaccuracies in the achieved orbit.

Various attempts towards development of guidance algorithm for a multi-stage solid motor propelled launch vehicle which facilitates precise orbit injection are being carried out. Waldemar de Castro Leite Filho and Pelson de Souza Pinto [1] proposed a Parametric Suborbit guidance (PSG) for the third stage and a Pointing Algorithm (PA) for the fourth stage along with open-loop guidance strategy for the first two stages of a four-stage solid propelled launch vehicle. With both PA and PSG in place, they were able to achieve an orbit accuracy of ± 100 km. Heng Xu and Wanchun Chen [2] proposed implicit excess energy management guidance strategies for solid launchers that can meet desired velocity in the pitch plane alone. Si-Yuan and Qun-Li Xia[3] proposed another implicit guidance

strategy which also tracks a spline generated on-board for excess energy management.

In this paper, the proposed guidance scheme is explained in section 2. Detailed discussions on first stage guidance is given in section 2.1 followed by guidance strategy for the second stage in section 2.2, guidance strategy for third stage in section 2.3 and guidance strategy for the terminal VCM phase in section 2.4. The proposed guidance scheme is validated for propulsion dispersion scenarios in all the stages and the results are discussed in section 3.

2. The Proposed Guidance Scheme

Guidance scheme for this multi-stage solid motor-powered launcher is developed such that the vehicle achieves required altitude and flight-path angle at third stage burn out. All performance dispersions accumulated since the first stage are transferred to SS3 burnout as dispersion in horizontal velocity alone. Thus, one of the apse (apogee/perigee) is met at third stage burnout and Velocity Correction Module (VCM) is used for circularization. In the second stage, energy management is achieved by targeting a sub-orbital coast-ellipse whose states are computed on-board based on vehicle performance. If the coast apogee targeted at second stage burn out is very much less, then a lower altitude is targeted at third stage burnout to conserve energy.

The proposed guidance scheme is represented as a block diagram in Figure 1.

The equations of motion for the exo-atmospheric phase of the launch vehicle in the local vertical-local horizontal (LVLH) plane is given as

$$\begin{aligned}\dot{u} &= a_T \cos(\alpha_R) \cos(\alpha_Y) \\ \dot{v} &= a_T \cos(\alpha_R) \sin(\alpha_Y) \\ \dot{w} &= a_T \sin(\alpha_R) + g_{eff}\end{aligned}\quad (1)$$

Where u, v and w are the velocity components in the LVLH frame (u along the local horizontal, w along local vertical and v along the angular momentum vector), a_T is the thrust acceleration and α_R and α_Y are the steering angles. g_{eff} is the effective gravity which is given by the equation

$$g_{eff} = \frac{\mu}{r^2} - \frac{u^2}{r} \quad (2)$$

Where μ is the gravity constant and r is the current radial distance of the vehicle.



Figure 1: The proposed Guidance Scheme

2.1. First Stage Guidance

During the first stage, vehicle has to clear the atmosphere, meeting aerodynamic load constraints. Conventional altitude-based steering generated on ground is stored on-board as a look up table. The vehicle will be steered with the open-loop steering commands obtained by interpolating the lookup table against the actual vehicle altitude.

2.2. Second Stage Guidance

During the second stage, velocity-based guidance scheme targets the horizontal and vertical velocity to achieve the desired coast ellipse. The guidance commands for steering the vehicle are computed from the target and current velocity components as follows:

$$\alpha_R = \arctan \left(\frac{w_f - w + g_{eff} t_{go}}{\sqrt{(u_f - u)^2 + (v_f - v)^2}} \right) \quad (3)$$

$$\alpha_Y = \arctan \left(\frac{v_f - v}{u_f - u} \right) \quad (4)$$

Where u_f, v_f and w_f are target velocities and t_{go} is the time to reach the target. The t_{go} value is taken as an initialization parameter instead of computing it on-board.

2.3. Third Stage Guidance

Required acceleration guidance achieves the target altitude and flight path angle at third stage burnout. The coast apogee is taken as a performance measure. If coast apogee is less than a predefined value, then coast apogee is targeted in the third stage to conserve energy.

In required acceleration guidance, the radial co-ordinate axis alone is controlled thereby meeting the altitude and radial velocity targets. The required acceleration along the radial axis assumed to be a linear function of time-to-go (t_{go}). In third stage also, t_{go} value is taken as an initialization parameter instead of computing it on-board.

The required acceleration along the radial direction is given by the equation

$$a_z = C_1 t_{go} + C_2 \quad (5)$$

Here the co-efficients C_1 and C_2 are computed in every guidance cycle till the stage burns out [7].

Once the required acceleration (a_z) is available, the steering angles α_R and α_Y can be computed as follows:

$$\alpha_R = \arcsin\left(\frac{a_z + g_{eff}}{a_T}\right) \quad (6)$$

$$\alpha_Y = \arctan\left(\frac{v_f - v}{u_f - u}\right) \quad (7)$$

2.4. VCM Phase Guidance

In VCM, since the acceleration level is low, ($0.6m/s^2$) burn durations are large resulting in gravity losses. An orbit transfer guidance scheme considering gravity losses is used to correct the velocity dispersions as well as the inclination errors in a single burn [4]. During the VCM Phase, the vehicle is steered along the velocity to be gained direction which is computed as given below.

$$\Delta \vec{V} = \begin{bmatrix} u_f \\ v_f \\ 0 \end{bmatrix} - \begin{bmatrix} u \\ v \\ w \end{bmatrix} + \frac{-g_{eff} t_{go}}{\Delta \theta} \begin{bmatrix} \cos(\Delta \theta) - 1 \\ 0 \\ \sin(\Delta \theta) \end{bmatrix} \quad (8)$$

Where $\Delta \theta$ is the radial angle covered by the vehicle during the VCM burn [5,6] which is given as

$$\Delta \theta = \frac{t_{go}}{2} \left(\frac{u}{r} + \frac{u_f}{r_f} \right) \quad (9)$$

The time-to-go (t_{go}) for the VCM Phase is computed on-board as

$$t_{go} = (\tau - t) \left(1 - e^{-\left(\frac{|\Delta V|}{V_e}\right)} \right) \quad (10)$$

Where V_e is the specific impulse of VCM, τ is the ratio of initial mass to mass flow rate and t is the phase time from VCM ignition.

3. Results and Discussions

The guidance algorithm was validated for a Low Earth Circular Orbit mission with altitude 356 km. For the nominal case, the orbit achieved at the third stage burnout was 392 x 356 km which was later corrected by VCM to 356km circular. The results corresponding to LB and UB propulsion is tabulated below.

Case	At 3 rd Stage Burnout		At VCM Burnout	
	Apogee (km)	Perigee (km)	Apogee (km)	Perigee (km)
Nominal	391.84	355.94	356.51	356.25
UB Thrust	520.64	356.00	357.29	356.39
LB Thrust	357.98	103.51	356.98	356.42

Table 1: Guidance performance for nominal, upper bound and lower bound propulsion

The apogee-perigee deviations for 350 simulation scenarios with propulsion dispersions ranging between additive LB and additive UB is given in Figure 2. The simulations clearly indicate that the proposed guidance scheme is capable of achieving precise orbit injection with a maximum (*apogee – perigee*) deviation of 3 km.

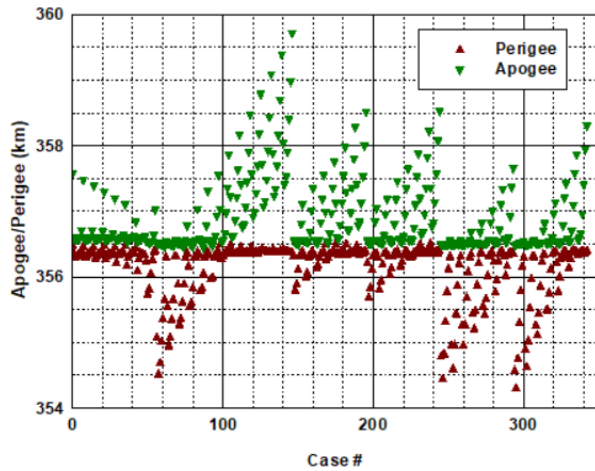


Figure 2: Orbit deviations at VCM Cutoff

The altitude and velocity profile of the vehicle for nominal and propulsion dispersion cases is given in Figure 3.

4. Conclusion

A guidance strategy with altitude based open loop steering in first stage, an explicit required velocity-based guidance in second stage, a required acceleration-based guidance in third stage and a gravity compensated low-thrust orbit transfer guidance for VCM phase was developed for a three-stage solid motor-powered launch vehicle. The guidance scheme was implemented for a Low Earth Circular Orbit Mission of altitude 356 km and the scheme was validated for nominal, upper bound and lower bound propulsion dispersions. The guidance scheme was observed to be robust in meeting the target orbit conditions for a wide range of propulsion dispersions.

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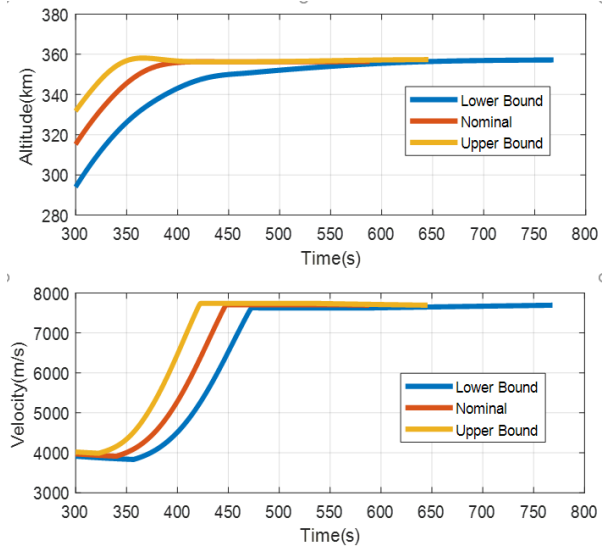


Figure 3: Altitude and Velocity Profile during Third Stage and VCM Phase for Nominal, UB and LB propulsion

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